1970

Antimatter

Claudia Morgan Griffin
Ouachita Baptist University

ANTIMATTER

Presented to
Dr. Clark W. McCarty
Ouachita Baptist University

In Fulfillment
of the Requirements for
Physics H492

---

by
Claudia Morgan Griffin
Spring 1970

#274

ANTIMATTER

Very little is known about the mysterious world of antimatter. The idea that such particles could exist was not even proposed until forty years ago. Perhaps the story of the discovery of antimatter began when scientists were trying to unify the Theory of Relativity and the Theory of Quanta. The trouble was that the quantities in the classical wave equation are in second derivitives:

$$\frac{\partial^2 u}{\partial x^2},\ \frac{\partial^2 u}{\partial y^2},\ \frac{\partial^2 u}{\partial z^2},\ \text{and}\ \frac{\partial^2 u}{\partial t^2}$$

In Schrödinger's wave equation of the Quantum Theory, x, y, and z are second derivatives, but t is a first derivative.[1]

Following Einstein's basic ideas, H. Minkowski proposed the concept of a four-dimensional time-space continuum in which time is multiplied by i ($\sqrt{-1}$) and is regarded as equivalent to the three space coordinates x, y, and z. For dimensional reasons, time is also multiplied by c, the velocity of light in a vacuum. O. Klein and W. Gorden tried to turn Schrodinger's equation into relativistic form simply by introducing the second derivatives on time. However, attempts to introduce the electron spin into this equation did not work.[2]

---

[1] George Gamow, Thirty Years that Shook Physics: The Story of Quantum Mechanics (Garden City, New York: Doubleday and Company, Inc., p. 4.

[2] Ibid., pp. 123-125.

Paul Adrien Maurice Dirac, a British physicist, in 1928 reasoned that if using the second derivative on the time coordinate did not work, then using the first deriviatives on the space coordinates might. This linear equation was successful.[3]

From Einstein's formula $E = mc^2$ and the relativistic mass formula $m = \frac{m_0}{\left(1-\frac{v^2}{c^2}\right)^{1/2}}$, we get

$$E = \frac{m_0{}^2}{\left(1-\frac{v^2}{c^2}\right)^{1/2}}$$

$$E^2 = \frac{m_0{}^2 c^4}{1-\frac{v^2}{c^2}} \qquad p^2 = \frac{m_0{}^2 v^2}{1-v^2 c^2}$$

$$E^2 = m_0{}^2 c^4 + p^2 c^2$$

where p = momentum = mv and E = the energy of a free, fast-moving electron. Dirac could see that there are two roots to this equation, a negative one and a positive one. This indicates that all particles have anti-particles. A particle can have an energy of $+m_0c^2$ or higher, or $-m_0c^2$ or lower, but it cannot have an energy between $-m_0c^2$ and $+ m_0c^2$.[4]

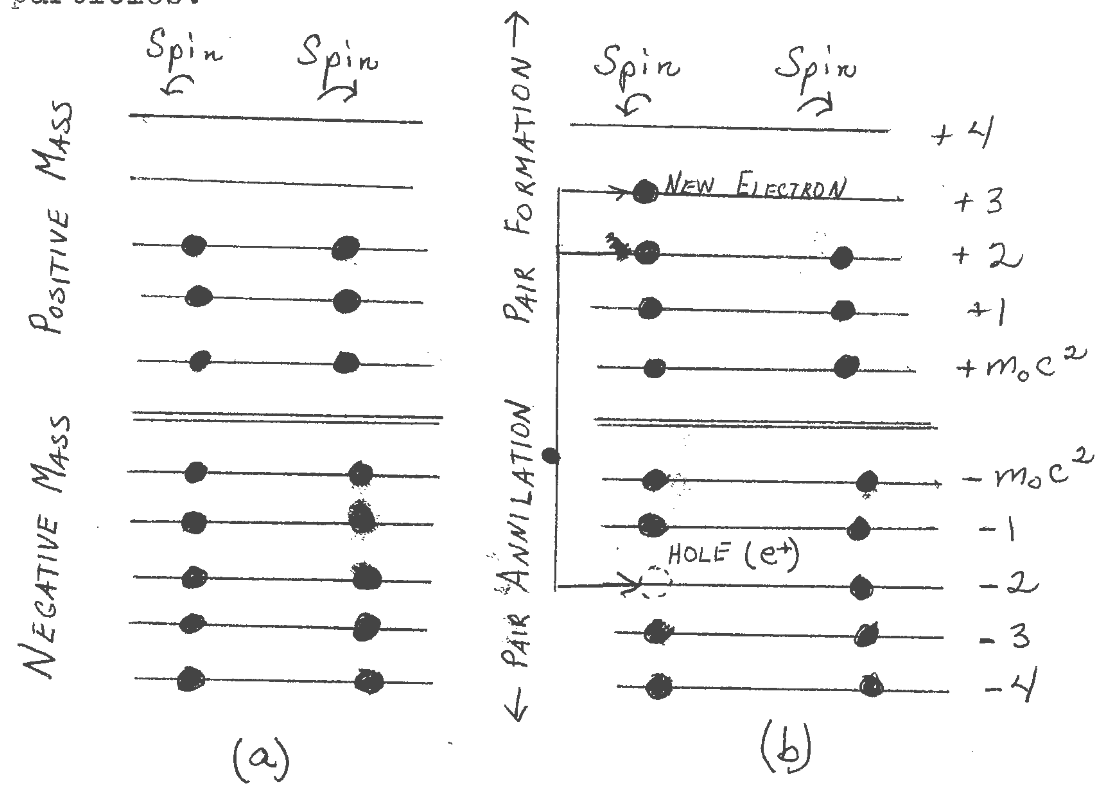
Dirac also deduced from the equation that a particle could have negative mass. This is how he qxplained anti-

---

[3] Ibid., p. 125.

[4] Derek L. Livesey, Atomic and Nuclear Physics (Waltham, Massachussets: Blaisdell Publishing Company, 1966), p. 138.

particles:



(a) All negative holes are filled up. Thus, 6 electrons and 0 positrons. (b) An electron from the negative level moves to the positive level, leaving a hole. Thus 7 electrons and 1 positron. If a negative electron falls into the hole (e- e+ annilation), the energy difference is given off as γ-radiation.[5]

Dirac's paper was published in 1930. There was violent opposition to his ideas. But around 1931 the American physicist Carl Anderson, studying cosmic-ray electrons passing through a strong magnetic field, observed that half of them

---

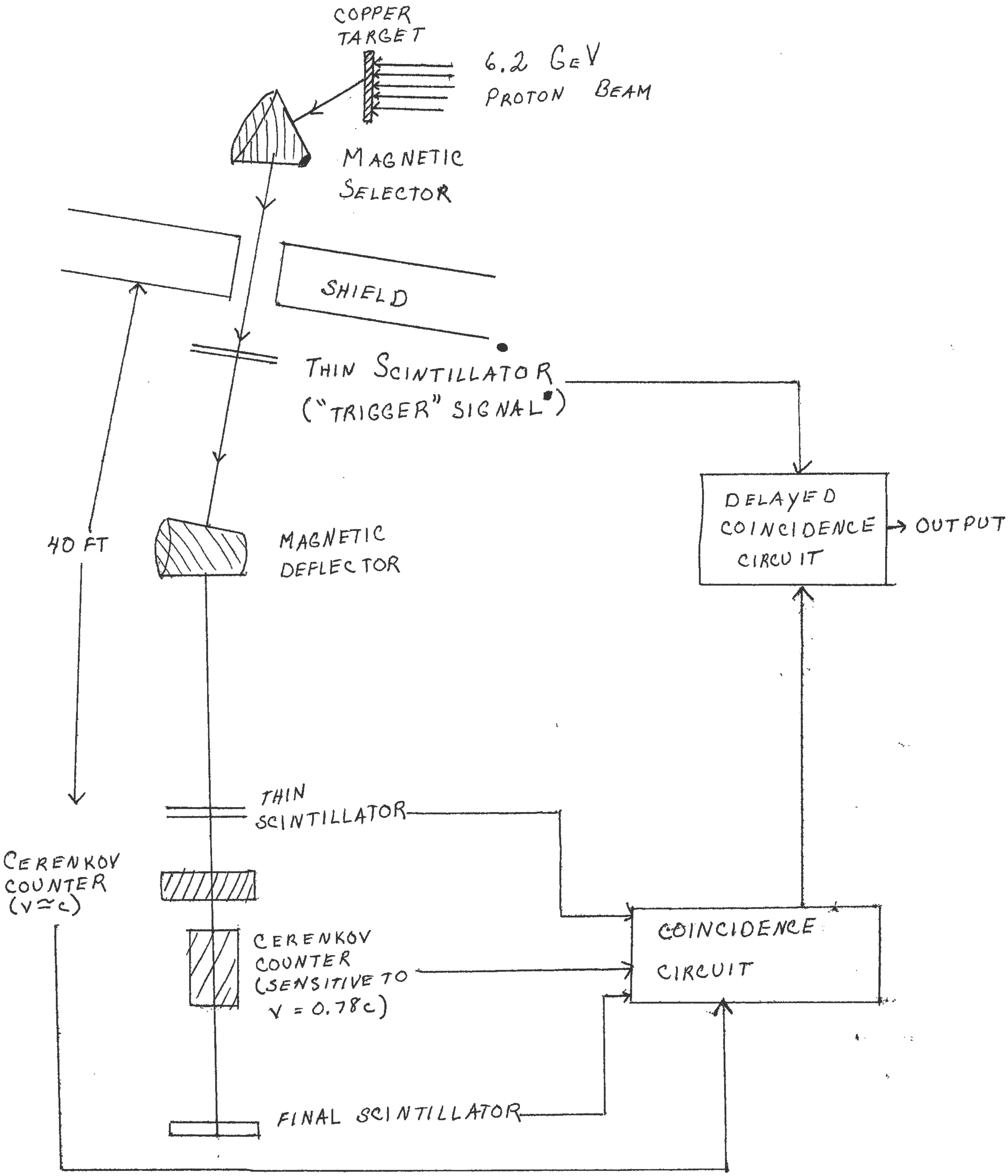
[5]Gamow, op. cit., pp. 126-130.

were deflected in one direction, and half in the opposite direction. The latter were positrons, positively charged electrons.[6]

In 1956 the antinuetron was detected. Also in 1956 the anti-proton was detected with the Bevatron at Berkeley. The energy needed in the center-of-mass coordinates of reacting particles in order to produce a proton pair is 1880 MeV ($\Delta E \rightarrow p^+ + p^-$). This is greater if the pairs are to be made in nucleon-nucleon collisions. In the laboratory system it must be at least 5.6 GeV. The first accelerator to reach this level was the Bevatron at Berkeley. Here antiprotons were identified among the products of high-energy reactions at 6.2 GeV. On the next page is a diagram of the Bevatron. A proton strikes a copper target. The negatively charged particles emitted from this are first passed through a magnetic-deflection system, which selects the particles with the proper momentum. These particles are focused into a beam passing through a heavy shield and into a thin scintillation counter. This counter acts as a trigger for a velocity-measuring system. The particles travel 40 feet in vacuo and are deflected again before reaching the final counter assembly. Here scintillation counters working in delayed coincidence with the first trigger counter sorted out the particles with the proper velocity--

---

[6]Gamow, op. cit., pp. 132-133.


COPPER TARGET
6.2 GeV PROTON BEAM
MAGNETIC SELECTOR
SHIELD
THIN SCINTILLATOR ("TRIGGER" SIGNAL)
DELAYED COINCIDENCE CIRCUIT
OUTPUT
40 FT
MAGNETIC DEFLECTOR
THIN SCINTILLATOR
CERENKOV COUNTER (v≃c)
CERENKOV COUNTER (SENSITIVE TO v = 0.78c)
COINCIDENCE CIRCUIT
FINAL SCINTILLATOR

Although Dirac first proposed the idea of antimatter, his picture of it was not totally accurate. Further study has shown that anti-particles have not negative mass, but positive mass. This is illustrated by the fact that when a particle and its anti-particle meet, mass is converted into energy. If the anti-particle had negative mass, the total mass for the pair would be zero, and no energy could be created.

What are some of the other properties of anti-particles? The charts on pages 7 and 8 outline the basic characteristics of different particles and anti-particles.

Anti-particles react with other anti-particles just as particles react with other particles. For example:

$$p + \pi^- \rightarrow n$$

$$\bar{p} + \pi^+ \rightarrow \bar{n}$$

They also decay similarly to ordinary particles:[7]

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$\bar{n} \rightarrow \bar{p} + e^+ + \nu_e$$

---

[7] Bruno Rossi, Cosmic Rays (New York: McGraw-Hill Book Company, 1964), pp. 258-260.

Particle	Rest Mass (MeV)	Decay Schemes	Mean Life (sec)
γ	0	Stable	
$\nu_e, \bar{\nu}_e$	0	Stable	
$\nu_\mu, \bar{\nu}_\mu$	≈ 0	Stable	
e^-, e^+	0.51101	Stable	
μ^-, μ^+	105.66	$e + \bar{\nu}_e + \nu_\mu$	2.200×10^{-6}
π^+, π^-	139.6	$\left\{ \begin{matrix} \mu + \nu_\mu \\ e + \nu_e \end{matrix} \right\}$	2.55×10^{-8}
π^0	135.0	$\left\{ \begin{matrix} 2\gamma \\ \gamma + e^- + e^+ \end{matrix} \right\}$	1.8×10^{-16}
K^+, K^-	493.8	$\left\{ \begin{matrix} 2\pi \\ 3\pi \\ \mu + \nu_\mu \end{matrix} \right\}$ and so forth	1.23×10^{-8}
K_1^0	498.0	2π	0.92×10^{-10}
K_2^0	498.0	$\left\{ \begin{matrix} 3\pi \\ \pi + \mu + \nu_\mu \\ \pi + e + \nu_e \end{matrix} \right\}$	5.6×10^{-8}
p^+, p^-	938.26	Stable	
$n, \bar{n}$	939.55	$p + e + \bar{\nu}_e$	1010
$\Lambda, \bar{\Lambda}$	1115.4	$\left\{ \begin{matrix} p + \pi^- \\ n + \pi^0 \end{matrix} \right\}$	2.62×10^{-10}
$\Sigma^+, \bar{\Sigma}^-$	1189.4	$\left\{ \begin{matrix} p + \pi^0 \\ n + \pi^+ \end{matrix} \right\}$	0.79×10^{-10}
$\Sigma^0, \bar{\Sigma}^0$	1192.3	$\Lambda^0 + \gamma$	$< 1.0 \times 10^{-14}$
$\Sigma^-, \bar{\Sigma}^+$	1197.1	$n + \pi^-$	1.6×10^{-14}
$\Xi^0, \bar{\Xi}^0$	1314	$\Lambda^0 + \pi^0$	3.1×10^{-10}
$\Xi^-, \bar{\Xi}^+$	1320.8	$\Lambda^0 + \pi^-$	1.74×10^{-10}
Ω	1680	$\left\{ \begin{matrix} \Xi + \pi \\ \Lambda + K \end{matrix} \right\}$ and so forth	10^{-10}

[9] Livesey, op. cit., p. 504

MAIN GROUPS	PARTICLES	ANTI-PARTICLES
Photon (spin $\hbar$)	Photon (γ)	
Leptons (spin $\frac{1}{2}\hbar$)	Neutrino (ν_e)	Antineutrino ($\bar{\nu}_e$)
	Neutrino (ν_μ)	Antineutrino ($\bar{\nu}_\mu$)
	Electron (e^-)	Positron (e^+)
	Negatine muon (μ^-)	Positive muon (μ^+)
Mesons (spin 0)	Positive pion (π^+)	Negative pion (π^-)
	Neutral pion (π^0)	
	Positive kaon (K^+)	Nagative kaon (K^-)
	Neutral kaon (K^0)	Neutral kaon ($\bar{K}^0$)
Baryons		
(spin $\frac{1}{2}\hbar$)	Proton (p^+)	Antiproton (p^-)
	Neutron (n)	Antineutron ($\bar{n}$)
	Lambda hyperon (λ)	Antilambda ($\bar{\lambda}$)
	Sigma hyperons ($\Sigma^+, \Sigma^0, \Sigma^-$)	Antisigmas ($\bar{\Sigma}^-, \bar{\Sigma}^0, \bar{\Sigma}^+$)
	Xi hyperons (Ξ^-, Ξ^0)	Antixis ($\bar{\Xi}^+$ $\bar{\Xi}^0$)
(spin $\frac{3}{2}\hbar$)	Omega hyperon (Ω) (?)	Antiomega ($\bar{\Omega}$)

---

[8] Livesey, op. cit., p. 504.

Notice that the neutral neutron has an anti-particle, but the neutral pion does not. This is because the neutron has a magnetic effect and the pion, since it has no spin, does not. The neutron has an opposite magnetic effect from that of an anti-neutron.[10] The photon does have a spin, but there is no anti-neutral-pion or anti-photon which a neutral pion or a photon could meet and be annihilated.

When matter meets antimatter, 100% of the mass turns to energy. A proton-anti-proton pair creates 1870 MeV of energy.[11] An electron-positron pair creates 1.02 MeV. This is determined by the equations $e^+ + e^- \rightarrow 2\hbar\omega$ and $p^+ + p^- \rightarrow 2\hbar\omega$.[12]

A positron is slowed down by surrounding particles. It stops near an electron. They attract each other and form positronium, a positron-electron system. This exists for about 10^{-8} sec. Then the whole system vanishes in a flash of light--usually two photons. Each particle has rest energy $m_o c^2$, some positive kinetic energy due to rotation, and some negative electrical potential energy. The latter two may be neglected compared with the rest energy. Therefore, the

---

[10] David Park, Contemporary Physics (New York: Harcourt, brace and World, Inc., 1964), p. 86.

[11] Larkin Kerwin, Atomic Physics (New York: Holt, Rinehart, and Winston, Inc., 1963), p. 355.

[12] Livesey, op. cit., p. 109.

total energy is $2m_oc^2$. The center of the system is initially at rest, thus the total initial momentum is zero.[13]

If positronium decayed into only one photon, the energy of the photon E_p would equal the energy of the particles, or $2m_oc^2$. The momentum of the photon would then be E_p/c, or $2m_oc$. Since the momentum of the two particles was zero, and since a single photon must carry momentum, then positronium cannot decay into one photon. If two photons are created, they go in opposite directions, each one having an absolute momentum of m_oc. The vector sum is zero, and momentum is conserved. Over 99% of the time positronium decays into two photons. The rest of the time it decays into more than two.[14] Therefore the annihilation radiation of the electron-proton pair consists of two 0.51 MeV photons, and the annihilation radiation of the proton-antiproton pair consists of two 935 MeV photons.[15] In reverse, a gamma ray can be converted into an electron-anti-electron pair or a proton-antiproton pair. (This process was not observed until 1965).[16]

The creation of positive and negative electrons simultaneously when high-energy photons encounter matter has a

---

[13]Elisha R. Huggins, Physics I (New York: W. A. Benjamin, Inc., 1968), p. 408.

[14]Ibid., pp. 408-409.

[15]Livesey, op. cit., p. 109.

[16]Issac Assimov, The Universe (New York: The Hearst Corporation, 1966), p. 265.

threshold for electrons at a photon energy of 1.02 MeV (The equivilent of two electron rest masses). At higher energies $K(e+) + K(e-) \approx \hbar\omega - 1.02$ MeV, where K is the kinetic energy and $\hbar\omega$ is the photon energy. The threshold energy is that energy spent in creating the two particles.[17]

A photon in free space cannot create an electron pair bacause it will never have enough energy to supply the kinetic energy required for conservation of momentum. Usually it takes place in the field of an atomic nucleus. If a high-energy photon strikes a massive object, like a nucleus, the nucleus can absorb some of the photon's momentum, and the photon's energy can be converted into an electron pair. The nucleus recoils with the excess momentum given it by the photon. Then the nucleus loses some kinetic energy, but this is negligible when one compares the mass of the nucleus to that of the electron.[18]

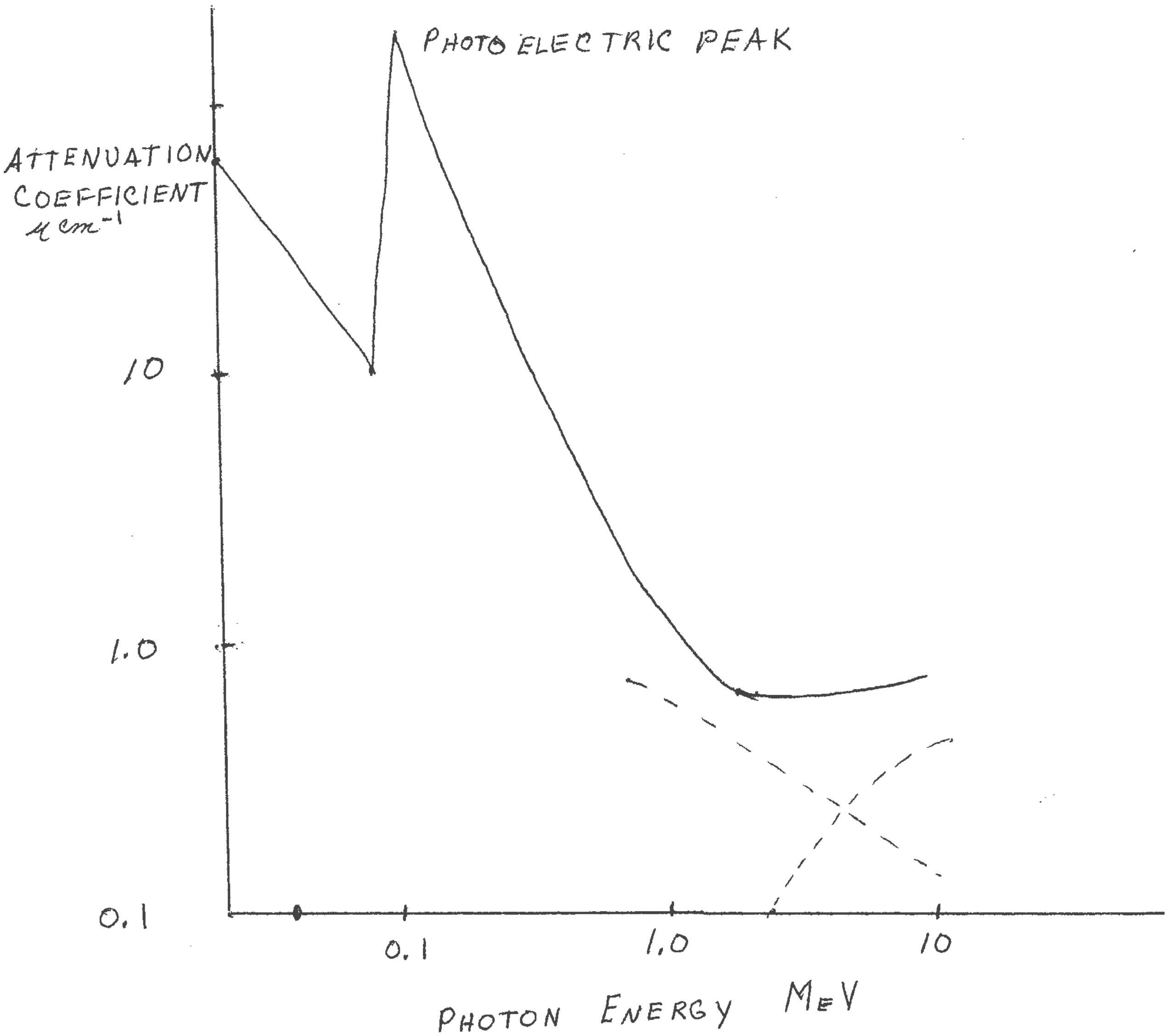
The larger the photon energy and the larger the atomic number of the atom, the greater the cross section for pair production. For instance, lead has an atomic number of 82. Pair production overcomes the Compton effect at 5 MeV, and it provides the greater part of the total attenuation cross

---

[17] Livesey, op. cit., p. 109.

[18] Ibid.

section above this energy. Notice that the total cross falls to a broad minimum in this region, then rises.[19]



[19] Livesey, op. cit., p. 109.

Microscopic study of matter has supported macroscopic study of the structure of the universe. Therefore, if there exists an anti-particle for every particle, they should be in equal numbers. These anti-particles make anti-atoms, which make anti-molecules, which make anti-stars. Half the universe, then is matter and half is anti-matter. But how do these two forms stay separated from each other? The Swedish physicist Oskar Klein suggested this theory:

Klein started with two basic premises: 1) "The universe at large is composed of equal quantities of matter and anti-matter." and 2) "It is governed by known physical laws, that is a plausible picture of such a universe can be drawn without postulating any new laws of nature." [20]

The first question, then, deals with the nature of the universe's evolution. The big bang theory says that the universe was created in the explosion of an extremely dense "ylem". If this ball had contained both ordinary matter and antimatter, it would have annihilated itself. The steady-state theory, based on the concept of continuous creation, also denies the creation of antimatter.[21] The steady-state theory says that matter could appear spontaneously with anti-

---

[20] Hannes Alfvén, "Antimatter and Cosmology," Scientific American, CCXVI (April,,1967), 106.

[21] Ibid., p. 107.

matter in continuous creation. But it seems that the gamma-radiation flux reaching the earth is a million times less than would be required by that theory.[22]

Klein's theory says that in its "initial state" the universe consisted of a very dilute spherical cloud of electrified particles and antiparticles.in uniform density. The cloud had a radius of a trillion light-years and the density of particles was no more than one per million cubic meters. At this distribution, the particles and anti-particles would practically never hit each other. When the universe radius had reduced to a few billion light years, some of the particles collided, releasing energy. When the universe got to about a billion light years in radius, it began to expand. This expansion was due to radiation pressure from the annihilation of particles overcoming the pressure of gravity. Regions of anti-matter and matter were formed because these were the particles that did not meet their opposites. A magnetized body of plasma surrounds each group of matter, and a magnetized anti-plasma surrounds each group of anti-matter. Protons and antiprotons spiral around the lines of the magnetic fields. Electrons and positrons annihilate each other. This forms a sort of curtain separating the two worlds. Possibly even stars within our own galaxy or the nearest galaxy are composed

---

[22] E. L. Schatzman, The Structure of the Universe, trans. Patrick Moore (New York: McGraw Hill Book Company, 1968), p. 236.

of antimatter.[23]

How can we detect matter stars from anti-matter stars? They both give off the same spectra, although they might show different Zeeman effects. But suppose the magnetic fields associated with matter have the opposite direction as those associated with antimatter. Then the effect would be the same. (The Zeeman effect is a splitting of spectral lines resulting from the action of a magnetic field on electrons.) Another way is by discovering specific emissions of energy from regions of antiplasma, where there is both matter and antimatter. This is detected in the form of radio emission. This could be an explanation for the mysterious quasars, which emit very great amounts of radio energy.[24]

Scientists have suggested other ways that anti-matter could be detected. Isaac Asimov suggests using cosmic rays. If an anti-particle has enough energy to escape its galaxy, it would have enough energy to be little affected by magnetic fields. Therefore anti-particle cosmic rays could be used to pinpoint anti-galaxies. Of course, how could we be sure that the anti-particles are really coming from anti-galaxies and not from pair production nearer to the earth?[25]

---

[23] Alfvén, op. cit., pp. 108-112.

[24] Ibid., p. 112.

[25] Asimov, op. cit., p. 265.

If scientists made contact with intelligent life on another planet, here is a way that they can determine of what kind of matter the planet is composed. The neutral eta meson is its own antiparticle. It decays into three pions--one negative, one positive, and one neutral. The positive pion carries more energy than the negative pion. This will happen both with matter and with anti-matter. In this way the positive charge can be defined, and scientists can tell us in mutual terms the charges of the particles on their planet.[26]

Scientists continue to explore the world of anti-particles. The "Alice-in-Wonderland" machine was designed for this purpose. It was devised one night in Siberia when two Soviet physicists, Gersh I. Budker and Stanislav N. Rodionov, were working on a proton-antiproton project. The machine accumulates a cloud of matter in a circular storage ring, accelerates it to almost the speed of light, and slams it into a cloud of matter. Once a particle is at the speed of light, any further acceleration does not increase speed, but does increase energy. So it is not as if these two particles hit each other at twice the speed of light. They hit each other at just under the speed of light, but at tremendeous energies.[27]

---

[26] Scientific American, "Bias for the Positive," CCXV (August, 1966), 40-42.

[27] News item in the New York Times, October 16, 1967.

The construction of the machine started in 1968. It covers an area of two city blocks. It should be in operation by 1970 or 1971. It is costing only $10-million--far less than conventional accelerators.[28]

With all the excitement and mystery of antimatter, there remains much humor. An example of this is the following poem written by the physicist Dr. H. P. Furth, now at Princeton, in 1956. It suggests what might happen if Dr. Edward Teller, a famous nuclear scientist who suggested that antimatter worlds exist, met his mirror image.

Peril of Modern Living

Well up beyond the tropostrata
There is a region stark and stellar
Where, on a streak of anti-matter
Lived Dr. Edward Anti-Teller.

Remote from Fusion's origin
He lived unguessed and unawares
With all his antikith and kin,
And kept macassars on his chairs.

One morning, idling by the sea,
He spied a tin of monstrous girth
That bore the letters A. E. C.
Out stepped a visitor from Earth.

Then, shouted gladly o'er the sands,
Met two who in their alien ways
Were like as lentils. Their right hands
Clasped, and the rest was gamma rays.[29]

---

[28] Ibid.

[29] Feature item in the New York Times, April 28, 1968.